

DYNAMIC FEATURES OF AUTODYNE SIGNALS

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UDC 621.373.122

On the example of classical single-circuit oscillator influenced by reflected signal, a solution of system of differential autodyne equations is obtained by the high-order quasi-static approximation method for the general case of arbitrary delay time of the reflected signal, fast motion of a point-sized reflecting object, and inertia of the oscillator itself. The special features of forming the autodyne response are considered with allowance for the oscillator inertia and its internal parameters, including anisochronous and non-isodromic properties, and dependences of the signal waveform, constant component, and nonlinear distortion coefficient on the distance and the direction of object motion are established.

Keywords: autodynes, autodyne oscillator, autodyne response, distortion parameter, autodyne response time constant, reflected signal, autodyne characteristics, direction of motion.

In short-range Doppler radar systems, due to the simplicity of their design and low cost of the microwave module, autodynes (autodyne oscillators) are often used combining simultaneously functions of generators of probing radiation and receivers of reflected signals [1, 2]. The operation principle of these devices is based on the autodyne effect peculiar to all oscillator types that is observed in the entire frequency range from radio to optical frequencies [2, 3]. This effect consists in changes of the self-oscillation parameters under the influence of reflected signals. Registration of these changes in the form of autodyne signals and their subsequent processing make it possible to obtain information on the reflecting object and parameters of its relative motion.

In the case of autodyne application for registration of the parameters of fast processes, for example, in experimental physics, combustion and explosion physics, indoor and outdoor ballistics, and other branches of science and technology [4, 5], one faces the problem of allowance for the inertia of these devices. A large number of works are devoted to an analysis of the special features of signal formation under such conditions. The influence of inertia of oscillation amplitude changes [6] and oscillator anisochronous property was analyzed in [3, 7]. In [8], in addition to the above-indicated oscillator properties, the non-isodromic oscillator property consisting in a dependence of the oscillation amplitude on the changes in the oscillation frequency was considered, and the special features of signal formation with allowance for the frequency dispersion of the autodyne frequency deviations and frequency auto-detection were studied. The condition of the validity of results of investigations common for the above-enumerated publications is a relatively short distances to the reflecting object for which the delay time τ of reflected signal is much less than the autodyne signal period T_a : $\tau \ll T_a$ [9].

However, for large distances to the reflecting object, high velocities of its motion, and short radiation wavelengths λ , the above inequality can be violated¹. To analyze autodyne operation under such conditions, one more

¹ For example, for 3-millimeter wavelength and radial object velocity $v_r = 2000$ m/s, the autodyne signal frequency, according to the Doppler formula $F_a = 2v_r / \lambda$, will be $F_a = 1.33 \cdot 10^6$ Hz, that is, the period will be $T_a = 0.75 \cdot 10^{-6}$ s. For the distance to the object $l = 120$ m, the time delay $\tau = 2l / c$ will be $0.8 \cdot 10^{-6}$ s, where c is the velocity of radiation propagation.

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inertia type caused by the signal propagation time to the reflecting object and back must be considered in the mathematical model of the system oscillator – reflecting object. As we know, the special features of forming the autodyne response were not considered in the literature under such conditions. To understand the processes occurring in the autodyne oscillator under the above-indicated conditions and to expand the field of autodyne application, it seems expedient to find a general solution of this problem.

In the present work, on the example of the classical single-circuit microwave oscillator with reflected signal, a solution is obtained of the system of differential autodyne equations using the high-order quasi-static approximation method for the general case of arbitrary delay time of the reflected signal, fast motion of the point-sized reflecting object, and inertial properties of the oscillator itself. Based on the results obtained, the special features of forming the autodyne response are considered with allowance for the internal oscillator parameters, such as anisochronous and non-isodromic properties, and dependences of the signal waveform, constant component, and nonlinear distortion coefficient on the distance and direction of object motion are established.

BASIC RELATIONS FOR AUTODYNE SIGNAL ANALYSIS

Using results of analysis of the single-circuit model of the autodyne oscillator with active element of the N -type (for example, the Gunn diode) [8] obtained in the approximation of small reflected signal excluding from consideration the auto-detection phenomenon, we write down a system of linearized differential equations for relative autodyne changes of the amplitude $a_1 = (A - A_0)/A_0$ and frequency $\chi = (\omega - \omega_0)/\omega_0$ of the oscillator:

$$(Q_L/\omega_n)(da_1/dt) + \alpha_{11}a_1 + \varepsilon_{11}\chi = \Gamma(t, \tau)\eta\cos\delta(t, \tau), \quad (1)$$

$$\beta_{11}a_1 + \xi_{11}\chi = -\Gamma(t, \tau)\eta\sin\delta(t, \tau), \quad (2)$$

where $A \equiv A(t)$ and $\omega \equiv \omega(t) = d\Psi(t)/dt$ are the current values of the oscillation amplitude and frequency depending on time; A_0 and ω_0 are their stationary values (at $\Gamma(t, \tau) = 0$); $\Psi(t)$ is the current oscillation phase; ω_0 and Q_L are the natural frequency and Q -factor of the loaded oscillator; $\alpha_{11} = (A_0/2G)(\partial G_{el}/\partial A)_0$ is the reduced slope of the oscillation increment defining the regeneration degree and the strength of the limit cycle in the vicinity of the stationary mode; $\varepsilon_{11} = (\omega_0/2G)(\partial G_{el}/\partial \omega)_0$ is the parameter of non-isodromic oscillator property [8, 10] or in other words, the influence factor of frequency variation onto the oscillation amplitude; $\beta_{11} = (A_0/2G)(\partial B_{el}/\partial A)_0$ is the parameter of anisochronous property; $\xi_{11} = \xi_{os} + \xi_{el}$ is the parameter of frequency stabilization taking into account the frequency slope of the oscillation system conductance $\xi_{os} = (\omega_0/2G)(\partial B_{os}/\partial \omega)_0 = Q_L$ and of the active element of the oscillator² $\xi_{el} = (\omega_0/2G)(\partial B_{el}/\partial \omega)_0$; $\Gamma(t, \tau) = \Gamma[A(t, \tau)/A(t)]$ and $\delta(t, \tau) = \Psi(t) - \Psi(t, \tau)$ are the modulus and phase of the instantaneous reflection coefficient reduced to the oscillator input-output, respectively; Γ characterizes the decay of the amplitude of radiation as it propagates to the object and back; $A(t, \tau)$ and $\Psi(t, \tau)$ are the oscillation amplitude and phase of the oscillator from the system prehistory ($t - \tau$); $\eta = Q_L / Q_{ext}$ and Q_{ext} are the efficiency and external Q -factor of the oscillating system; G_{el} and B_{el} are the active and reactive parts of the electronic conductance of the active element averaged over the oscillation period; and G is the total conductance of the resonator losses and oscillator load.

System of equations (1) and (2) differs from that used in [7] by the presence of the parameter ε_{11} that typically must be taken into account when analyzing millimeter-wave autodynes based on solid-state active elements [8, 10]. In addition, the function of influence onto the oscillator in system (1) and (2) is represented by the pure “transport” delay of the reflected signal.

² Because the inequality $\xi_{os} \gg \xi_{el}$ is satisfied for actual microwave oscillators, we further set $\xi_{11} = Q_L$.

From Eqs. (1) and (2) it can be seen that the main inertia of the autodyne systems is caused by changes of the oscillation amplitude. Combining these expressions and eliminating the variable χ , we obtain

$$da_1 / dt + (1 / \tau_a) a_1 = [\Gamma(t, \tau) \eta \omega_0 \sqrt{1 + \rho^2} / Q_L] \cos[\delta(t, \tau) - \psi_1], \quad (3)$$

where τ_a is the characteristic time constant (amplitude relaxation time [3]) of the autodyne response: $\tau_a = Q_L / [\alpha_{11} \omega_0 (1 - \gamma \rho)]$; $\gamma = \beta_{11} / \alpha_{11}$ and $\rho = \varepsilon_{11} / Q_{\text{load}}$ are non-isocronous and non-isodromic factors, respectively; and $\psi_1 = \arctan(\rho)$ is the angle of the phase shift of the autodyne amplitude changes.

The modulus $\Gamma(t, \tau)$ and the phase $\delta(t, \tau)$ of the reflection coefficient entering into Eqs. (1)–(3) are implicit functions. To derive them, according to the theory of systems with delay [11], we expand the amplitude, $A(t, \tau)$, and phase, $\Psi(t, \tau)$, functions of the reflected wave in Taylor series in the parameter τ small in comparison with the current time t :

$$A(t, \tau) = A(t) - \frac{\tau}{1!} \frac{dA(t)}{dt} + \frac{\tau^2}{2!} \frac{d^2 A(t)}{dt^2} - \frac{\tau^3}{3!} \frac{d^3 A(t)}{dt^3} + \dots, \quad (4)$$

$$\Psi(t, \tau) = \Psi(t) - \frac{\tau \omega(t)}{1!} + \frac{\tau^2}{2!} \frac{d\omega(t)}{dt} - \frac{\tau^3}{3!} \frac{d^2 \omega(t)}{dt^2} + \dots \quad (5)$$

The above formulas are valid under conditions of forming smooth autodyne changes of the oscillation parameters.

An exact solution of system of equation (1)–(3) with allowance for formulas (4) and (5) is absent. The quasi-static solution of this system valid when the strong inequality $\tau_a \ll T_a$ is satisfied does not consider the oscillator inertia [10]. In the theory of self-oscillating systems, a more exact method of finding a quasi-static solution of differential equations considering dynamics of changes of the influence function (see [12], p. 642) is well known. In the N th approximation, the solution obtained by this method for the autodyne amplitude, $a_1(t)$, and frequency, $\chi(t)$, variations has the form

$$a_1(t) = \Gamma(t, \tau) K_a K_{1\Omega}^{(N)} \cos(\delta(t, \tau) - \psi_1 - \psi_\Omega), \quad (6)$$

$$\chi(t) = -\Gamma(t, \tau) L_a L_\Omega^{(N)} \sin[\delta(t, \tau) + \Theta_\Omega^{(N)}], \quad (7)$$

where K_a and L_a are the autodyne gain and the frequency deviation coefficient of the oscillator:

$$K_a = \eta \sqrt{1 + \rho^2} / [\alpha_{11} (1 - \gamma \rho)], \quad L_a = \eta \sqrt{1 + \gamma^2} / [Q_L (1 - \gamma \rho)],$$

$K_{1\Omega}^{(N)}$ and $L_\Omega^{(N)}$ are the dynamic autodyne gain and the dynamic frequency deviation coefficient for oscillations depending on the normalized oscillator frequency $\Omega_n = \tau_a \Omega_a$ in the N th approximation:

$$K_{1\Omega}^{(N)} = \sqrt{1 + \Omega_n^2} \sum_{n=0}^{N-1} (-1)^n \Omega_n^{2n}, \quad L_\Omega^{(N)} = [(X_1^2 + X_2^2) / (1 + \gamma^2)]^{1/2}, \quad (8)$$

$\psi_\Omega = \arctan \Omega_n$ and $\Theta_\Omega^{(N)} = \arctan [X_2(\Omega_n) / X_1(\Omega_n)]$ are the dynamic phase shift angles of autodyne variations depending on the frequency, and $X_1(\Omega_n) = 1 - \gamma \rho + \gamma(\rho + \Omega_n) \sum_{n=0}^{N-1} (-1)^n \Omega_n^{2n}$ and $X_2(\Omega_n) = \gamma(1 - \rho \Omega_n) \sum_{n=0}^{N-1} (-1)^n \Omega_n^{2n}$ are the orthogonal components of the autodyne frequency deviation. Equations (6) and (7) in the first approximation for

$N = 1$ coincide with the corresponding expressions for the autodyne response obtained in [8] based on solving Eqs. (1) and (2) under assumption of linear phase variations.

From Eqs. (6) and (7) with allowance for expansions (4) and (5) after simple transformations and convolution of the series we obtain expressions for the phase $\delta(t, \tau)$ and normalized variations of the oscillation amplitude $a_{1n}(t)$ and frequency $\chi_n(t)$ of the oscillator of the form

$$\delta(t, \tau) = \Psi(t) - \Psi(t, \tau) = \omega_0 \tau - p_\Sigma \sin[\delta(t, \tau) + \theta + \Theta_n(\Omega_n)] - K_\Gamma L_\Omega^{(N)} Y_\Sigma^{(I)} \tau \sin[\delta(t, \tau) - \psi_1 + \Theta_i(r_n)], \quad (9)$$

$$a_{1n}(t) = a_1(t) / a_{1m} = K_{1\Omega}^{(N)} \cos[\delta(t, \tau) - \psi_1] + K_\Gamma K_{1\Omega}^{(N)} Y_\Sigma^{(I)} \sin[\delta(t, \tau) - \psi_1 + \Theta_i(r_n)], \quad (10)$$

$$\chi_n(t) = \chi(t) / \chi_m = -L_\Omega^{(N)} \sin[\delta(t, \tau) + \theta] - K_\Gamma L_\Omega^{(N)} Y_\Sigma^{(I)} \sin[\delta(t, \tau) - \psi_1 + \Theta_i(r_n)], \quad (11)$$

where $p_\Sigma = p_a p_d$ is the equivalent parameter of autodyne response distortions whose physical meaning is the signal phase modulation coefficient [13], $p_a = \omega_0 \chi_m \tau$ is the initial distortion parameter (quasi-static in the first approximation) of the autodyne response [9, 10], $p_d = L_\Omega^{(N)} Y_\Sigma^{(I)}$ is the dynamic multiplier of the distortion parameter, $Y_\Sigma^{(I)} = \sum_{i=0}^I (-1)^i Y_i(r_n)$ is the I th order amplitude multiplier, $a_{1m} = \Gamma K_a$ and $\chi_m = \Gamma L_a$ are the relative amplitudes of the corresponding autodyne variations, $r_n = \tau / T_a$ is the parameter of the normalized relative period T_a of the autodyne signal for the distance to the reflecting object, $\theta = \arctan(\gamma)$ is the phase shift angle of the autodyne frequency variations, K_Γ is the *amplitude multiplier* of the autodyne characteristics under the influence of reflected signal:

$$K_\Gamma = \{2\pi r_n a_{1m} \cos[\delta(t, \tau) - \psi_1]\} / \{1 + a_{1m} \cos[\delta(t, \tau) - \psi_1]\}, \quad (12)$$

$Y_i(r_n)$ and $\Theta_i(r_n)$ are the amplitude coefficients of the series and their phases, respectively:

$$Y_i(r_n) = \left[(2\pi r_n)^2 \sqrt{4(i+1)^2 + (2\pi r_n)^2} \right] / [2(i+1) \cdot (2i+1)!], \quad (13)$$

$$\Theta_i(r_n) = -\arctan[\pi r_n / (i+1)]. \quad (14)$$

From Eqs. (9)–(12) it follows that in the case of small signal when $a_{1m} \ll 1$, the last terms in Eqs. (9)–(11) can be neglected. Below we analyze exactly this case setting $\Gamma(t, \tau) = \Gamma$. Such approximation in the mathematical autodyne model takes into account the phase delay of reflected signal. By analogy with [10], we find a solution of transcendental equation (9) by the method of successive approximation. Provided that the equivalent distortion parameter is $p_\Sigma < 1$, this solution in the form of the autodyne phase characteristic (APC) $\delta(\tau_n)$ has the form

$$\begin{aligned} \delta(\tau_n) = & (2\pi\tau_n)_{(0)} - p_\Sigma \sin[(2\pi\tau_n)_{(1)} + \theta + \Theta_i(r_n)] \\ & - p_\Sigma \sin[(2\pi\tau_n)_{(2)} + \theta + \Theta_i(r_n)] \dots - p_\Sigma \sin[(2\pi\tau_n)_{(k)} + \theta + \Theta_i(r_n)] \dots \end{aligned} \quad (15)$$

where the subscripts in the parentheses adjacent to $(2\pi\tau_n)$ designate the approximation order, and $\tau_n = \omega_0 \tau$ is the normalized (dimensionless) time.

A linear phase characteristic typical of the homodyne systems in which the oscillator and the antenna are typically separated corresponds to zero approximation of Eq. (15). Higher order approximations introduce nonlinearity in this dependence, which is peculiar to the autodyne systems and is caused by frequency variations. Taking the derivative of Eq. (15) with respect to the normalized time τ_n and considering that functions $Y_i(r_n)$ and $\Theta_i(r_n)$ are

slowly varying ones, we obtain the expression for the k th order approximation of the normalized instantaneous frequency difference $\Omega_{an}(\tau_n)$ between the transmitted and reflected oscillations on the external autodyne oscillator load:

$$\begin{aligned}\Omega_{an}(\tau_n) &= [d\delta(\tau_n) / d\tau_n] / 2\pi = 1 - (p_\Sigma / 2\pi) \{ \cos[(2\pi\tau_n)_{(1)} + \theta + \Theta_i(r_n) \\ &\quad - p_\Sigma \sin[(2\pi\tau_n)_{(2)} + \theta + \Theta_i(r_n) - \dots - p_\Sigma \sin[(2\pi\tau_n)_{(k)} + \theta + \Theta_i(r_n)] \dots] \} \\ &\quad \times \{ 1 - p_\Sigma \cos[(2\pi\tau_n)_{(2)} + \theta + \Theta_i(r_n) - \dots - p_\Sigma \sin[(2\pi\tau_n)_{(k)} + \theta + \Theta_i(r_n)] \dots] \} \times \dots \\ &\quad \times \{ 1 - p_\Sigma \{ \cos[(2\pi\tau_n)_{(k)} + \theta + \Theta_i(r_n)] \dots \} \} .\end{aligned}\quad (16)$$

Further analysis of these expressions, because of their complexity, we perform by the numerical method with application of the mathematical software package *MathCAD*.

CALCULATION AND ANALYSIS OF THE AUTODYNE CHARACTERISTICS

Figure 1 shows results of calculations of APC and $\delta(\tau_n)$ and their normalized derivatives $\Omega_{an}(\tau_n)$ together with the autodyne frequency (AFC) $\chi_n(\tau_n)$ and amplitude characteristics (AAC) $a_{n1}(\tau_n)$ using Eqs. (9)–(11) with allowance for Eqs. (13)–(16). Calculations were performed for the following values of the parameters: $\gamma = 1$, $\rho = -0.2$, $p_a = 0.8$, $\Omega_n = \pm 0.8$, $N = 10$, and $I = k = 50$ for the normalized distances $r_n = 0$ (Fig. 1a) and 0.5 (Fig. 1b). We note that the convergence of the calculated results for the above-indicated values of I , k , and N was provided for $|\Omega_n| \leq 0.8$, $r_n \leq 5$, and $p_a \leq 0.98$, respectively. For the reflector moving away, the curves in Fig. 1 are denoted by figures 1, and for the approaching reflector, they are denoted by figures 2. Below we name sections according to normalized ranges r_n , multiple to integers and corresponding to the working zones, starting from the first range for which $0 \leq r_n \leq 1$.

An analysis of Eqs. (6)–(16) and characteristics shown in Fig. 1 demonstrates that for small normalized distances to the reflector when $r_n \ll 1$, the results obtained here coincide completely with the dynamic characteristics calculated previously (see Fig. 4 of [8]). The special features of forming the autodyne response [8] were considered only in the first approximation disregarding the dynamics of oscillation frequency and amplitude variations by setting $\Gamma(t, \tau) = \Gamma$ and $\delta(t, \tau) = \omega\tau$.

The nonuniform phase shift $\delta(\tau_n)$ of the reflected wave (see Fig. 1a) that causes distortions of the characteristics AFC $\chi_n(\tau_n)$ and AAC $a_{n1}(\tau_n)$ is caused by variations of the autodyne frequency $\chi_n(\tau_n)$. These distortions are manifested through changes of “wave slopes” of the autodyne characteristics depending on the direction of reflector motion and on the internal oscillator parameters [8, 10]. The degree of distortion of the characteristics depends on the direction of reflector motion, which is caused by the dependence of the magnitude of autodyne frequency deviations on the sign of the Doppler shift (frequency dispersion of the autodyne frequency deviations [7]). The average oscillation frequency offset for the period of the autodyne response and the distance $r_n \ll 1$ is absent, and the oscillator response on the amplitude variation contains the constant component whose polarity depends on the sign of the non-isodromous parameter ρ , and its value is determined only by the distortion parameter.

The rate of change of the APC phase shift $\delta(\tau_n)$ characterized by the instantaneous difference of the frequencies $\Omega_{an}(\tau_n)$ of transmitted and reflected signal is oscillating in character with the formation of *peaks* of the instantaneous frequency. The peak height increases with the distortion parameter p_a which, in turn, also depends on the internal oscillator parameters, level of the reflected signal, and direction of object motion. It should be noted that these oscillations of the instantaneous frequency $\Omega_{an}(\tau_n)$ are observed given that its average value for the autodyne response period remains unchanged and equal to the Doppler frequency.

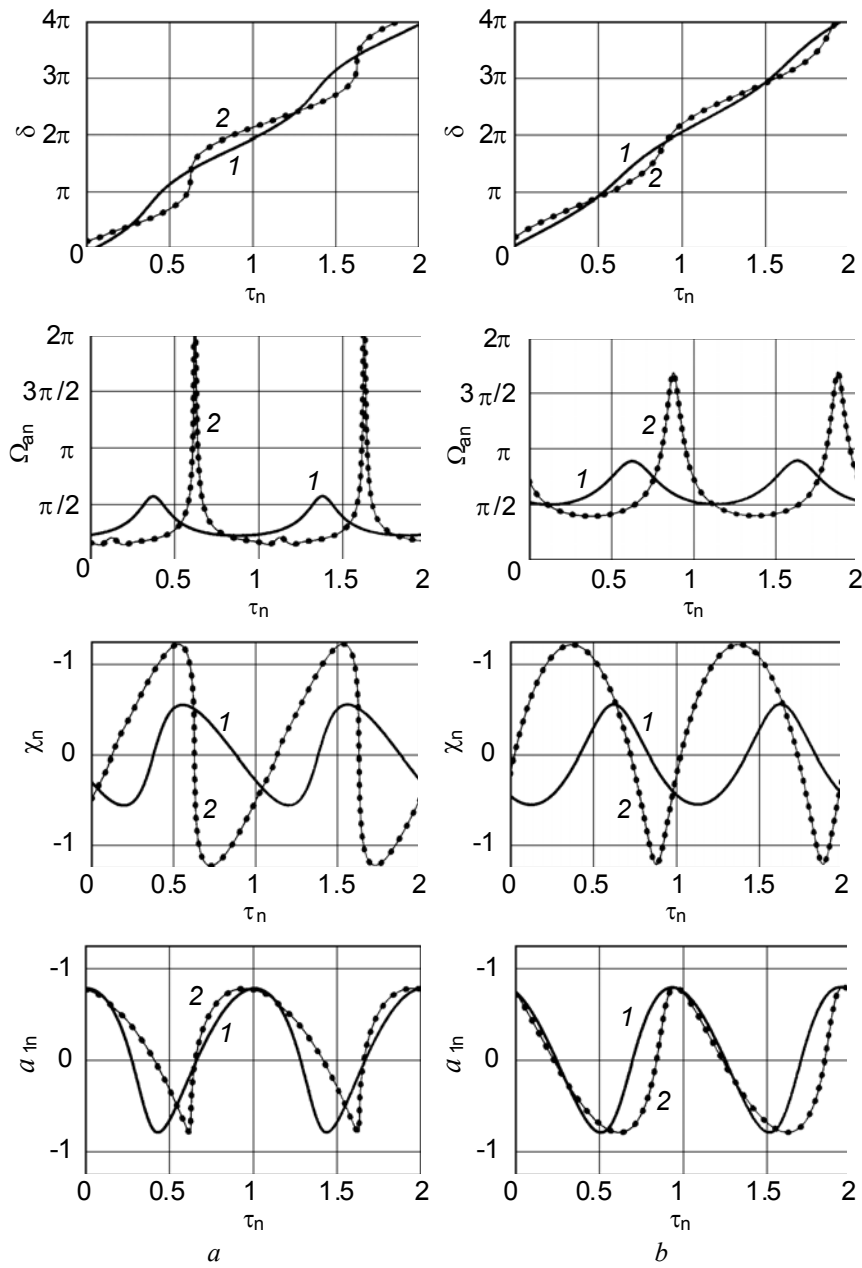


Fig. 1

Proceeding to an analysis of the characteristics shown in Fig. 1, we note that with increasing normalized distances r_n , the waveforms of the AFC $\chi_n(\tau_n)$ and AAC $a_{1n}(\tau_n)$ differ significantly from those observed in the preceding case by the degree of their distortions when $r_n \ll 1$ and by the additional phase shift. A more detailed analysis of these characteristics is presented below. Here we note only that calculations for other r_n values demonstrated that when $r_n = 1, 2, \dots, m$, where m is integer, the AFC and AAC have the waveforms close to sinusoidal ones; moreover, the APC $\delta(\tau_n)$ is a linear function of τ_n , and the instantaneous frequency difference is $\Omega_{an}(\tau_n) = 1$.

A decrease in the degree of nonlinearity of the APC $\delta(\tau_n)$ and hence heights of instantaneous $\Omega_{an}(\tau_n)$ frequency peaks with increasing distance r_n (see Fig. 1) indicates the decrease of the equivalent distortion parameter

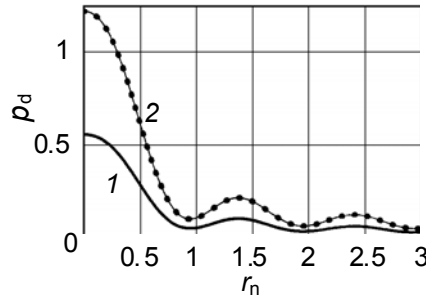


Fig. 2

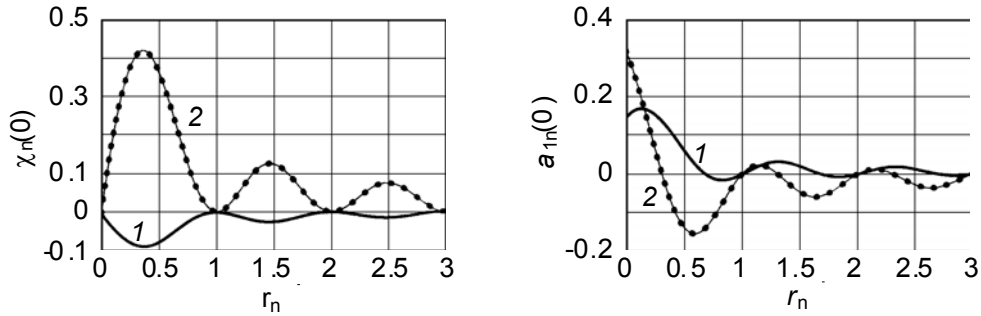


Fig. 3

p_{Σ} due to its dynamic factor p_d . From the plot of the dependence of this factor p_d on the normalized distance r_n shown in Fig. 2 it can be seen that with increasing normalized distance r_n in the first working zone, where $0 < r_n < 1$, the value of the equivalent distortion parameter p_{Σ} decreases by more than 5 times. Furthermore, with increasing r_n , the p_d value asymptotically decays with a small increase in the central section of higher order working zones, where $r_n > 1$. As can be seen from these plots, the degree of *suppression* of the distortion parameter depends also on the sign of the velocity vector of the object.

Figure 3 shows plots of the dependences of relative values of constant components of changes of autodyne frequency $\chi_n(0)$ and amplitude $a_{in}(0)$ on the normalized distance r_n to the reflecting object. Calculations were carried out for moving away (curves 1) and approaching objects (curves 2), $p_a = 0.8$, and γ and ρ values indicated above.

Plots of dependences of harmonic coefficients of normalized changes in the frequency $K_{\Gamma\chi}$ and amplitude $K_{\Gamma a}$ of oscillations of the autodyne oscillator on the relative distance r_n to the reflecting object are shown in Fig. 4. The nonlinear distortion coefficients were calculated for the amplitudes of the first ten harmonic components of expansion in the Fourier series for the moving away (curves 1) and approaching (curves 2) reflecting object.

The characteristic $\chi_n(0)$ calculated as a function of the normalized distance r_n (Fig. 3) for different parameters of non-isochronous parameter γ and non-isodromous parameter ρ of the oscillator demonstrated that its waveform is independent of the internal parameters of the oscillator and is determined by the value of the equivalent distortion parameter p_{Σ} . The given characteristic is a positive function for the approaching object that corresponds to the positive Doppler shift and is negative (inverted) for the object moving away when the negative Doppler shift is observed. In this case, it should be noted that no relationship of the average frequency offset $\chi_n(0)$ with the Doppler frequency offset was observed. The presence of the constant component in the AFC $\chi_n(\tau_n)$ and the change of its polarity are well illustrated by curves in Fig. 1b. Maximum offsets of the average value $\chi_n(0)$ (see Fig. 4) are observed

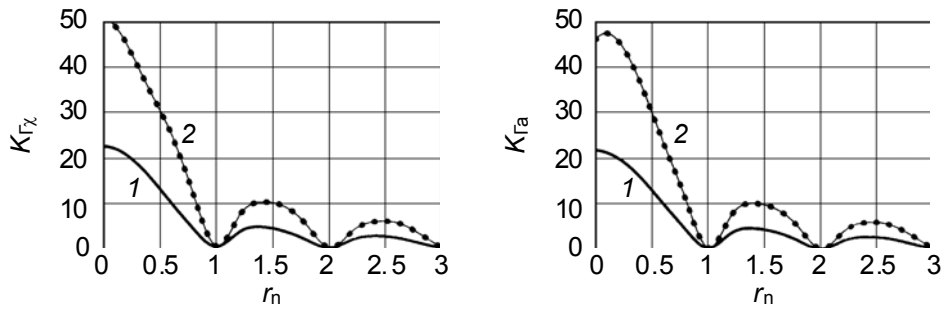


Fig. 4

in the first working zone at the distance $r_n = 0.4$; they are $\chi_n(0) = 0.41$ for the approaching object and $\chi_n(0) = 0.08$ for the object moving away. For integer values of the normalized distance ($r_n = 0, 1, 2, \dots$), the constant component of frequency variations is absent irrespective of the value and sign of the object velocity.

As can be seen from the plots drawn in Fig. 3, the average value of the relative variations of the autodyne amplitude $a_{n1}(0)$ is a sign-alternating function of the normalized distance r_n ; as a rule, it alters its polarity once in each working zone. Calculations with other values of γ and ρ demonstrated that the value of the constant component $a_{n1}(0)$ and its polarity for some ranges of distances r_n depend on the direction of reflector motion. In the case of isochronic and isodromic oscillator with $\gamma = \rho = 0$ and in the case of integer values of the relative distance ($r_n = 0, 1, 2, \dots$), such dependence on the direction of motion of the reflecting object is absent, since the autodyne characteristics at these points are harmonic, and the phenomenon of frequency dispersion is absent for the autodyne frequency deviations.

The dependences of the harmonic coefficients of relative frequency, $K_{\Gamma\chi}$, and amplitude, $K_{\Gamma a}$, variations of autodyne oscillations of the oscillator on the normalized distance r_n to the reflecting object (see Fig. 4) are in good agreement with the analogous dependence of the dynamic multiplier p_d of the distortion parameter (see Fig. 2). At points where the normalized distance is equal to an integer ($r_n = 0, 1, 2, \dots$), the harmonic coefficients are $K_{\Gamma\chi} = K_{\Gamma a} = 0$.

An analysis of the calculated results demonstrates that if in the beginning of the first zone, where $r_n \ll 1$, the value of the distortion parameter p_a exceeds its boundary value even several times, stable operation of autodyne oscillators with formation of quasi-sinusoidal signals for high velocities of reflecting object motion can be provided in higher order working zones. When $p_\Sigma \ll 1$, the AFC and AAC, as usual, are harmonic functions, and APC is practically linear.

Direct experimental investigations of the revealed special features of autodyne signals are difficult due to complexity and high cost of creation of natural conditions at which large distance to the object and simultaneously supersonic velocity of its motion must be provided [14]. The waveforms of autodyne signals presented in [15] for moving away and approaching object qualitatively coincide with those of the AAC obtained in the present work and hence confirm the efficiency of the developed model and the correctness of calculated results.

CONCLUSIONS

The results of investigations of the dynamic autodyne characteristics for the case when the period of autodyne response is commensurable with or even less than the delay time of the reflected signal have shown that the distortion level of autodyne signals decreases with increasing distance to the reflecting object for the hypothetical case in which the reflected wave amplitude remains unchanged. The method of calculating the dynamic characteristics of microwave

autodyne oscillators based on the application of the high order quasi-static approximation that considers the inertia of oscillation amplitude variations and frequency dispersion of the autodyne frequency deviation was developed.

It was demonstrated that the level of distortions of the characteristics depended not only on the internal properties of the oscillator and value of the distortion parameter, but also on the direction of reflecting object motion. Results obtained in this work can be used in calculation of signals of not only microwave autodyne oscillators, but also, from our point of view, of autodyne laser systems measuring the object velocity³ [1]. In addition, they can find application in analysis of the special features of autodyne signals of perspective systems of radar sensing of the atmosphere [16]. In these systems, the distance to the balloon with autodyne receiver-responder onboard can be so large (250 km) that to receive radio signals of the request radar and to provide sufficient accuracy of measuring the distance and velocity, the phenomena revealed in the present study should be taken into account.

This work was supported in part by the Ministry of Education and Science of the Russian Federation under Governmental Decree No. 218 from September 4, 2010.

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³Thus, for example, for laser wavelength of about 900 nm, we have the output autodyne signal frequency of about 20 MHz, which is provided for object velocity of about 10 m/s. In this case, at a distance of only 10 m, the signal period ($T_a = 45 \cdot 10^{-9}$ s) appears less than the delay time of the reflected signal ($\tau = 55.7 \cdot 10^{-9}$ s).